A Composite TE-TFE-FE Model for Schottky Barrier Reverse Current over the Entire Electric-Field Range

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Introduction:

Schottky barriers in wide bandgap (WBG) semiconductors sustain very large electric fields under reverse bias due to the access of very large barrier heights (>1 eV) and the very high intrinsic breakdown field (>3 MV/cm) of WBG semiconductors [1]. Under high surface electric-fields (E), the ideal reverse-bias leakage current (J₀) is dominated by barrier tunneling rather than thermionic emission (TE), thus thermionic-field-emission (TFE) or field-emission (FE) becomes the dominant mechanism [1][2]. Therefore, to accurately describe the reverse current over the entire surface electric-field range, TFE and FE models are required in addition to the TE model.

We have recently developed a unified TE-TFE model that covers the entire TE and TFE regimes [3], however, the model is not applicable in the FE regime, the same goes for all other stand-alone TFE models. On the other hand, the well-known Murphy-Good FE model works well in the FE regime [2], but it is not applicable in the TFE regime. As a result, a gap exists in the TFE-to-FE transition region, as illustrated in Fig. 1, where no good analytical model exists. There has been an attempt to derive a unified TFE and FE model, however, the model is based on highly simplified emission integration with questionable accuracy, and image-force lowering is ignored [4]. In this context, we present a simple composite analytical model that covers the entire E-field range with excellent accuracy, with the use of an empirically-derived extrapolation function in the TFE-to-FE transition region.

Methods:

The integral for the barrier tunneling current under reverse bias is analytically intractable in the TFE-to-FE transition region, which means that a result, a gap exists in the TFE-to-FE transition region, as illustrated in Fig. 1, where no good analytical model exists. There has been an attempt to derive a unified TFE and FE model, however, the model is based on highly simplified emission integration with questionable accuracy, and image-force lowering is ignored [4]. In this context, we present a simple composite analytical model that covers the entire E-field range with excellent accuracy, with the use of an empirically-derived extrapolation function in the TFE-to-FE transition region.

Results and Discussion:

Comparisons between the composite TE-TFE-FE model relative to the reference numerical model [1] is shown in Fig. 5. The log error across the entire E-field range is within 2 dB (equivalent to a factor of 1.25) (Fig. 2c). The first derivative also shows very good agreement with the numerical model (Fig. 2b), indicating the extrapolation function for J_trans allows for a smooth transition between TFE and FE. We have used the composite model to analyze the reverse leakage characteristics in near-ideal 4H-SiC SBDs [6] and Ga2O3 SBDs [1]. Very good agreement between experimental data and the composite model is observed across both the TE/TFE and FE regimes, with the barrier height as the only fitting parameter (Fig. 6). Such an accurate analysis over the entire temperature and surface electric-field range is only possible with numerical calculations previously, as illustrated in Table 1.

Conclusion:

The composite TE-TFE-FE model successfully bridges the gap between the unified TE-TFE model and the Murphy-Good FE model with a simple empirical extrapolation function, allowing for accurate modeling of the Schottky barrier reverse current across the entire electric-field range. The closed-form and local nature of the composite model allows for easy implementation in TCAD tools for device design and analysis.

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References:

Fig. 1. (a) Illustration of the TE/TFE regime and the FE regime. Unified TE-TFE [3] and Murphy-Good FE [2] models both have limited applicable range. (b) Definition of $J_1$, $J_2$, $E_1$ and $E_2$ in the new composite model.

Fig. 3. Main equations for the composite TE-TFE-FE model.

- $J_R = \begin{cases} J_{TFE} + J_{FE}, & \text{if } 0 < E \leq E_{lim,TFE} \\ J_{trans} & \text{if } E_{lim,TFE} < E < E_{lim,FE} \\ J_{FE}, & \text{if } E \geq E_{lim,FE} \end{cases}$

- $J_{TFE} + J_{FE}$: unified TE-TFE model [3]
- $J_{FE}$: Murphy-Good FE model [2]
- $J_{trans}$: transition region between TFE and FE

Fig. 4. Modified conditions for $E_{lim,TFE}$ and $E_{lim,FE}$ in the composite model with improved accuracy.

- Eq. 10 in Ref. 3 for $E_{lim,TFE}$
- $\left(1 + \frac{3}{2} - 1\right)^{-1} < \phi_F - \alpha_1$
- $\alpha_1$ is increased from 1 to 4 for improved accuracy.
- Eq. 58 in Ref. 2 for $E_{lim,FE}$
- $1 - \frac{c_{1/2}T}{\epsilon_0} > (2\alpha_1)^{1/2} \frac{m^*}{\epsilon_0}$
- $\alpha_1$ is increased from 2 to 6 for improved accuracy. $\epsilon_D = \frac{m^*e^2}{(4\pi \alpha_1)^2h^2}$ is the Bohr energy constant.

Fig. 5. The composite model exhibits excellent agreement against the reference numerical model [1].

**Legend:**
- $\phi_B = 1.3$ V, $m^* = 0.3 m_0$, $\epsilon_S = 10 \epsilon_0$.

**TABLE I.** Comparison of different models applicable at the FE regime.

<table>
<thead>
<tr>
<th>Model</th>
<th>Temperature dependence</th>
<th>Image-force lowering</th>
<th>Entire E-field range</th>
<th>Closed-form expression</th>
<th>Doping effect</th>
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<td>No</td>
<td>Yes</td>
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<tr>
<td>Murphy-Good FE [2]</td>
<td>Yes</td>
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<td>Unified TFE-FE</td>
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<td>Numerical model [1]</td>
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<td>No</td>
<td>No</td>
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</table>

*Insignificant below $1 \times 10^{11}$ cm$^3$.

Fig. 6. Analysis of near-ideal reverse leakage characteristics in (a) 4H-SiC SBDs [6] and (b) $\beta$-Ga$_2$O$_3$ SBDs [1] using the composite model, with the barrier height as the only fitting parameter.